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Spectroscopic Determination of Electron Temperature and Percentage Ionization in a Helium Plasma

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THE spectroscopic diagnostic technique presented for determining electron temperature is a refinement of the method of Cunningham, Frieman, and Harm.[1] The results obtained with this technique will be strictly valid in a low-pressure, high-temperature, so-called tenuous plasma,[2] and will be invalid in a plasma where local thermodynamic equilibrium is obtained. In general, the method utilizes the observed excitation cross sections for certain helium singlet and triplet spectral lines that are known over a range of electron energies. These cross sections are then averaged over the electron velocity distribution of the plasma which is assumed to be Maxwellian. From the ratio of these averaged cross sections the intensity ratio of the spectral lines may be plotted versus electron kinetic temperature.

In reference 1, the observed spectral lines were the singlet 2^1P–4^1D(4921 Å) transition and the triplet 2^3P–4^3S(4713 Å) transition. The cross-section data were taken from Lees.[3]

The electron kinetic temperatures obtained by observing the relative intensities of these transitions may be misleading, however, because of errors inherent in the cross sections.

Gabriel and Heddle[4] have indicated that an error in absolute-intensity calibration exists in Lees' investigation. The relative magnitudes of these cross sections may also be in error, since some values will be enhanced by the effects of secondary processes due to the relatively high pressure (44 μ) used in his investigation.

The extent to which these secondary processes affect the cross section determination depends upon the pressure in the collision chamber, and, therefore, the observed cross section would be expected to vary with pressure. Lin and St. John[5] have shown that the 4^1D excitation function changes considerably in both shape and magnitude as the pressure varies from 5.8 to 130 μ. Consequently, the observed intensity ratio of the spectral lines used in reference 1 would vary with pressure, even though the electron kinetic temperature were to remain constant.

Since the method presented by Berger[6] for determining the percentage ionization in a helium plasma also utilizes Lees' cross section data and the observation of the 4921 Å radiation, it will also yield misleading results.

In recent experiments, St. John[7] has shown that the excitation cross sections for the n^1S and n^3S levels are relatively insensitive to pressure in the range of 0 to 130 μ. On the basis of these results, a spectroscopic diagnostic scheme is presented in which the electron temperature is determined from the observed intensities of 2^1P–n^1S and 2^3P–n^3S transitions, and the percentage ionization is calculated from the relative intensities of the 2^1P–4^1S(5047 Å) neutral line and the 4686 Å He II line.

The intensity of a j-k transition I_{jk} is given by the relation

$$I_{jk} = N_0 N_e Q_{jk}(V) V, \tag{1}$$

where N_0 is the neutral density, N_e is the electron density, V is the electron velocity, and $Q_{jk}(V)$ is the excitation cross section for the j-k transition. If there is a distribution of electron energies, Eq. (1) becomes

$$I_{jk} = N_0 N_e \langle Q_{jk}(V) V \rangle. \tag{2}$$

The brackets indicate a value averaged over the distribution.

Thus, the intensity ratio x_0 of two spectral lines is given by the relation

$$x_0 = \frac{I_{jk}}{I_{mn}} = \frac{N_0 N_e \langle Q_{jk}(V) V \rangle}{N_0 N_e \langle Q_{mn}(V) V \rangle} = \frac{\langle Q_{jk}(V) V \rangle}{\langle Q_{lm}(V) V \rangle}. \tag{3}$$

Similarly, the intensity ratio of the 4686 Å He II line and the 5047 Å He I line x_+ is given by

$$x_+ = \frac{I_{4686}}{I_{5047}} = \frac{N_i N_e \langle Q_{4686}(V) V \rangle}{N_0 N_e \langle Q_{5047}(V) V \rangle} = \frac{N_i \langle Q_{4686}(V) V \rangle}{N_0 \langle Q_{5047}(V) V \rangle} \tag{4}$$

where N_i is the ion density. Letting

$$F(kT_e) = \langle Q_{4686}(V) V \rangle / \langle Q_{5047}(V) V \rangle,$$

Eq. (4) becomes

$$x_+ = (N_i/N_0) F(kT_e) \tag{5}$$

From the definition of the percentage ionized P and Eq. (5), it is seen that

$$P = \frac{100 N_i}{N_i + N_0} = \frac{100}{1 + \dfrac{F(kT_e)}{x_+}} \tag{6}$$

The excitation functions used for the neutral helium lines incorporate the results of a number of previous investigations[4,8–10] and are discussed in detail by Sovic.[11] These excitation functions have been empirically fit with equations representing the excitation cross section as a function of electron velocity, multiplied by the electron velocity, and averaged over a Maxwellian distribution to obtain the quantities $\langle Q_{jk}(V) V \rangle$ and $\langle Q_{mn}(V) V \rangle$.

The 4686 Å line corresponds to a 4–3 transition in He II. The quantity $\langle Q_{4686}(V) V \rangle$ is taken from Berger[6] who has calculated this cross section by scaling the hydrogen cross sections for exciting the "4" levels and multiplying by the branching ratios of Bethe.[12]

Now that the averaged cross sections have been obtained, the quantities $F(kT_e)$ and x_0 are plotted against electron temperature in Figure 1.

In order to obtain the electron temperature and the percentage ionized, one merely needs to observe the intensity ratio x_0 of the indicated neutral lines and obtain the electron temperature and $F(kT_e)$ from Fig. 1. The percentage ionized is then calculated by using the observed x_+ and Eq. (6).

In experimental electron kinetic temperature measurements in a radio-frequency discharge ($n_e \cong 10^{11}$, $kT_e \cong 15$ eV) fair agreement has been obtained between spectroscopically determined tem-

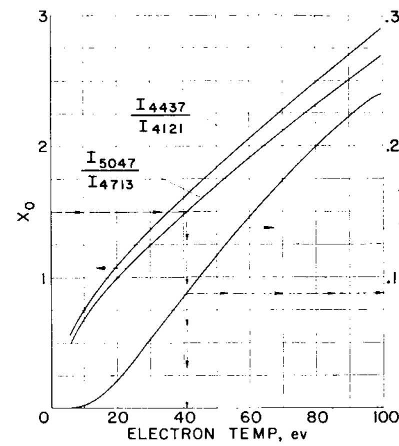

FIG. 1. Variation of X_0 and $F(kT_e)$ with electron kinetic temperature.

peratures using the I_{5047}/I_{4713} ratio and those obtained by using conventional floating double probe techniques. Detailed comparisons have not been made, however, since the probes become exceedingly hot and have short lifetimes in the plasma.

Another possible application of the above mentioned technique would be to measure electron kinetic temperatures in a plasma that is lightly seeded with helium. Initial experimental investigations using seeded plasmas have shown that in some cases the spectrum lines of the parent gas will overlap the helium lines. In order to alleviate this observational difficulty the I_{4437}/I_{4128} ratio has also been presented on figure 1 as a function of electron kinetic temperature.

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